

TIME AND FREQUENCY KEEPING AND ITS DISTRIBUTION SYSTEM AT CRL

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Abstract

As a national frequency standards laboratory in Japan, Communications Research Laboratory (CRL) is doing research and development work on a primary frequency standard. Besides the primary standard, CRL is in charge of the generation of local UTC, UTC(CRL), and its time and frequency distribution via HF and LF radio signals, telephone line, and computer network. CRL contributes to TAI not only atomic clock data, but also as one of the node laboratories of the international GPS time transfer network of the BIPM. For this purpose CRL is studying the GPS ionospheric measurement system and two-way time transfer using communication satellites. In this paper we will present activities on time and frequency standards at CRL.

1 INTRODUCTION

Communications Research Laboratory (CRL) has a long history, more than 50 years, involving time and frequency standards, and several remarkable results were achieved. But after around the epoch when its name was changed from RRL (Radio Research Laboratory) to CRL, the number of researchers in time and frequency were reduced because of several reasons. One of them was that CRL shifted and expanded its research area to communication and information engineering. Another one was that CRL performed research and development on applications of time and frequency standards.

At present we are considering how to do basic research work and service on time and frequency standards to contribute to science, engineering, and social life. In this paper we describe the present and near future activities in the field of time and frequency at CRL. Work in this field falls into following areas:

- developing primary frequency standards,
- determining and keeping frequency and time standards,
- disseminating frequency and time standards, and
- comparing standards to those established by organizations in foreign countries. And the following basic research activities will support the above items:
 - research and development of technology for precisely measuring frequency and time,
 - theoretical research.

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE DEC 1996		2. REPORT TYPE		3. DATES COVERED 00-00-1996 to 00-00-1996	
4. TITLE AND SUBTITLE Time and Frequency Keeping and its Distribution System at CRL				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Communications Research Laboratory,4-2-1, Nukuikita-machi, Koganei,Tokyo, 184 Japan,				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES See also ADA419480. 28th Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting, Reston, VA, 3-5 Dec 1996					
14. ABSTRACT see report					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 13	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

2 TIMEKEEPING AT UTC(CRL)

2.1 Primary Atomic Frequency Standard^[1-5]

(1) Optically Pumped Cesium Standard

Research on Cs standards at CRL has been inactive in the last few years due to several reasons. In order to reactivate and prompt the research, a joint research project on an optically pumped cesium-beam-type frequency standard was contracted with National Institute of Standards and Technology (NIST) of the USA in January 1996. In this project, we aim to establish a primary frequency standard with accuracy of several parts in 10^{-15} until 1998 and will contribute to the accuracy of TAI at the level of 10^{-15} .

The standard is based on NIST-7 and several important improvements will be made. One of them is the adoption of an anti-resonance mode ring cavity, which is expected to have very low dimensional sensitivity of end-to-end phase difference and to result in high accuracy. It has never previously been adopted in primary Cs standards and its performance is anticipated with great interest.

(2) Cesium Fountain Standard

The recent progress in laser cooling and trapping technology has enabled a cesium-fountain-type frequency standard using very cold atoms to be developed. It is very promising as a future primary standard with an accuracy of $10^{-15} \sim 10^{-16}$, since the use of low-velocity atoms and a single cavity reduces or eliminates most of the frequency shifts such as second order Doppler shift or cavity end-to-end phase shift, which limit the accuracy of the Cs-beam-type standard. Due to this great advantage in accuracy evaluation, many institutes of time and frequency standards have recently started researching fountain standards. Indeed, LPTF in France has developed a fountain-type standard and succeeded in achieving an accuracy of 3×10^{-15} .

We have also started preliminary experiments in order to establish the basic technologies required for a fountain standard, and succeeded in trapping and cooling cesium atoms down to several microkelvins in a gas cell. As a next step, we plan to launch cold atoms upward in 1996.

After establishing these technologies, we will start designing and developing a fountain standard in 1997.

2.2 Timekeeping Using Commercial Clocks^[6-8]

About 10 cesium atomic clocks are working to generate UTC(CRL) at CRL. The TA(CRL) calculation algorithm was established for generating a time scale at CRL in 1978. The algorithm requires that the short-term and long-term fluctuations of each clock be separated with a digital filter. Each clock is then weighted for short- and long-term stability to average out the fluctuations. And the evaluation method of unbiased Allan variances from biased ones was also studied. These results were applied to calculation of the TA(CRL) as a paper time scale.

In 1985, a real-time UTC(CRL) generation method, illustrated in Figure 1, was developed from the conventional master clock method for generating UTC (CRL). This method uses a weighted-average technique which incorporates microphase steppers. With the current UTC(CRL), a time difference of less than 100 ns and a frequency difference of better than 1×10^{-14} is kept against UTC.

3 TIME AND FREQUENCY DISSEMINATION

3.1 HF and LF Standard Time Emission

At CRL, one of the main methods of disseminating frequency and time standards is time signal emission using the shortwave band, JJY, and the longwave band, JG2AS. JJY has been used ever since transmissions were started in 1940. These signals are currently transmitted from NTT's Nazaki Station (located in Sanwa-machi Sashimagun, Ibaraki Prefecture). Since there had been problems with the accuracy of the disseminated frequency and with interference, CRL's inner committee was organized to discuss the future plan of standard time and frequency dissemination during 1993 and 1994. The following steps were proposed as a result of this committee's work.

- (a) Strengthen emission power of the standard long-wave band and establish it as the proper standard frequency station.
- (b) Gradually decrease the use of the standard shortwave band, and eventually abolish its use as a standard.
- (c) Establish a dissemination method for frequency and time standards that is suitable for the multimedia age.

In response to item (b), of the conventional five standard shortwave bands (2.5, 5, 8, 10, and 15 MHz), two were eliminated (2.5 and 15 MHz) in 1996.

As for item (a), although JG2AS is still in an experimental stage, the number of radio-controlled watches and clocks that receive JG2AS in Japan already exceeds 300,000. Its dissemination accuracy is on the order of 10^{-11} or 10^{-12} . CRL has requested funds to construct a new longwave station. This new station will have more than 5 times stronger emission power compared with the present one. If CRL can obtain the funds, the new station will begin operation in 1999.

3.2 Telephone Line Service of Standard Time^[9]

As for item (c) of the previous section, several dissemination methods are currently being researched, such as Telephone JJY, Network Time Protocol, and FM radio broadcasting. The most representative of these is a time information service using telephone lines, called the Telephone JJY, which started public service in August 1995. Telephone JJY was started after basic experiments had been conducted over several years. It uses commercial telephone lines and has a loop-back function which enables compensation of the line and circuit delay on the user side. Users can calibrate clocks to the Japanese Standard Time within an accuracy of 1 ms using the loop-back function. Telephone JJY is used by various broadcasting stations to

calibrate master clocks and for disseminating time as a replacement for JJY. Because the number of PC networks is expanding, uses per month as of October 1996 reached as much as 21,000. The number of uses is increasing at a rate of almost 2,000 a month. Figure 2 shows the number of users of Telephone JJY since August, 1995.

3.3 NTP Server of UTC(CRL)^[10]

Since the rapid spread of computer networks such as the Internet, time synchronization among the computers connected to the network is very important. The NTP (Network Time Protocol) is an excellent technique to the computer network such as the Internet. However, there are several problems when a UNIX workstation is used as a server: the time resolution, the nature of multi-tasking, the I/O port problem, and the property of asymmetry of I/O path delays.

CRL's NTP stratum-1 server connected to UTC(CRL) under development is based on an IBM-compatible PC with a specially designed ISA bus board for a time code generator, and modified NTP protocol, which works for MS-DOS. Some of the problems described above are improved by this server. This work is being cooperatively performed with one of the Internet providers in Japan and it will be in service in 1997.

4 TIME TRANSFER

4.1 GPS Time Transfer^[11-12]

In order to contribute the atomic clocks of CRL to TAI and UTC and to clarify the relationship between UTC(CRL) and UTC, CRL is conducting routine time transfer using GPS satellites according to the BIPM observation schedule which is used by major world time and frequency research institutes.

During 1987 and 1988, a CRL researcher conducted cooperative research at BIPM on an ionospheric total-electron-content measurement receiver based on the GPS dual-frequency P-code signal cross-correlation (this device is GTR-2, which is commercially available as TECmeter). The device is used to compensate for ionospheric delays in time comparisons.

As shown in the Figure 3, CRL is operated as one of three major nodes of the international GPS time transfer network for BIPM, and plays an important role in TAI computations. Thus, CRL contributes to TAI not only by atomic clock data, but also as one of the node laboratories of the international GPS time transfer network of the BIPM.

4.2 Two-Way Satellite Time Transfer^[13-14]

Two-way satellite time transfer (TWSTT) using a communications satellite (ATS-1) was achieved in 1975 at a precision of 1 ns between Japan and the United States. This involved the successful detection of the relativistic Sagnac effect caused by the earth's rotation. In 1983, TWSTT experiments were conducted in Japan on the

Ka-band (20/30 GHz band) using an experimental communications satellite (CS).

These experiments, however, were interrupted for some time by problems in securing international satellite links due to problems in the facilities in the partner country. Beginning in 1992, however, international TWSTT experiments were resumed using the INTELSAT satellite. With CRL taking the initiative, experiments were conducted between Japan and Taiwan (Telecommunications Laboratory), and Japan and Korea (Korean Research Institute of Standards and Science). CRL has a Mitrex modem 2500A and an original one which is compatible with the Mitrex modem developed at CRL, and two Ku (12/14 GHz) band ground stations with 1.8-m dish antennas. The experiments were conducted at a precision of 1 ns.

The preparation work is currently underway for a joint experiment between Japan and Australia (CSIRO-NML) during 1996-1997. We will also conduct TWSTT experiments with the United States, and try to establish a key time transfer station in the Asian region.

4.3 Time Transfer Using High-Speed Digital Network

Under cooperative study with Nippon Telegram and Telephone Co. (NTT), precise time transfer experiments are being performed. This research is using a high-speed digital network, which has a data transmission rate of 2.4 Gbps. It uses a physical layer of SDH level and has a possibility of time transfer precision of ns level using the two-way method. A time-transfer experiment is being made between CRL Koganei headquarters and NTT Optical Network Systems Laboratories; the distance is about 70 km. We are planning to make simultaneous time-transfer experiments using this method and two-way satellite time transfer beginning in 1997.

5 RELATED RESEARCH WORK

5.1 Pulsar Timing Observation⁽¹⁵⁻¹⁷⁾

Many researchers are now paying close attention to pulsars, especially millisecond pulsars, which have a millisecond rotation rate. These pulsars are believed to be even better than the atomic frequency standard on earth in terms of long-term stability on the order of a year. As a research application of the 34-meter antenna constructed at the Kashima Space Communication Center in 1988, CRL initiated a project in 1989 with the main objective of developing applications to time scales of the properties of these pulsars.

Currently, the most accurate pulsar timing measurements are performed by the 305-meter ground-fixed antenna at the Arecibo Observatory in Puerto Rico. Since the 34-meter antenna at CRL collects 1/80th the amount of light as the Arecibo antenna, we are studying the development of measurement equipment that will compensate for this low light collection capability by broadening the observation frequency band and extending the observation time.

We started out with measurement equipment based on a total bandwidth of 4 MHz which has a 16-channel filter bank, before developing 50 MHz, 256-channel obser-

vation equipment which uses an acoustic optical spectrometer (AOS) along with a dedicated averaging device. A schematic diagram of the measurement system using AOS is shown in Figure 4. We are currently evaluating the capability of this equipment. If it performs to its full design potential, we think we will be able to make observations with an accuracy of 1 microsecond or less for PSR-1937+21.

5.2 Theoretical Research the Relativistic Effects^[18-20]

The relativistic effects due to the earth's orbital motion and solar gravity that affect the earth's proper time and frequency standards can be as large as 10^{-8} . Even near the earth, the velocity of a satellite and the effects of the earth's gravity can cause frequency fluctuations on the order of about 10^{-10} . Therefore, in order to use stable frequency standards that are as accurate as 10^{-14} , we have to consider relativistic effects.

In 1990, CRL conducted a theoretical investigation of time geostationary orbits, where a flying body will have the same proper time as the bodies on the earth's geoid surface. Since then, we have been engaged in theoretical research concerning the precise measurement of time and space. We have also been conducting collaborative research with the National Astronomical Observatory and Tohoku University, resulting in the development of a formula which simultaneously determines the mass and distance of a single star by considering the gravitational lens effect and the effects of gravitational delay on the arrival time of pulse signals from a pulsar due to massive interstellar bodies.

The following projects are part of ongoing theoretical research on relativistic effects:

1. A study of the effects of interstellar gravitational fields on the construction of reference frames and pulsar time scales.
2. A study of relativistic effects on two-way satellite time transfer, lunar geodesy, and planetary geodesy.

5.3 Basic Research and Development of the Future GNSS^[21]

According to a statement of the President of the United States in March 1996, the use of GPS after 2005 is guaranteed. Since the main purpose of GPS system is for the military, the next-generation GNSS (Global Navigation Satellite System) should be constructed independently of the military under international cooperation. We will start to develop several key technologies to contribute this next-generation GNSS:

- A spaceborne hydrogen maser. The development of a spaceborne hydrogen maser requires the size and weight of the maser to be reduced considerably. We plan to develop a maser that weighs 50–100 kg and has a stability at the 10^{-15} level. There are two approaches to satisfying the requirements; one is to use a full-sized microwave cavity, which is being developed at the Smithsonian Astronomical Observatory, and the other is to use a small-sized cavity such as a sapphire-loaded cavity or a loop-gap-type cavity.
- Precise time and frequency transfer between a spaceborne hydrogen maser and a ground-based clock at the 10^{-15} and 0.1–0.01 ns levels.

6 APPLICATION OF TIME AND FREQUENCY STANDARDS^[22]

For the application area of the time and frequency standards, CRL is doing research and development in VLBI (Very Long Baseline Interferometry) and SLR (Satellite Laser Ranging). One of the biggest projects in this field is the Crustal Deformation Monitoring System in the Tokyo Metropolitan Area. It has four sets of VLBI and SLR stations around the Tokyo metropolitan area to monitor the geodetic movement precisely. The station locations are illustrated in Figure 5. We already finished the VLBI facilities and started the observations. Precise time and frequency is one of the most important technologies for this project. We are also studying a real time VLBI using high-speed digital communication links in cooperation with NTT.

7 CONCLUSION

The situation of time and frequency standards at CRL has not been very active for at least the past few years. Meanwhile, the accuracy of the top level of the frequency standards is reaching the order of 10^{-15} . In addition, needs of the society and industry for the time and frequency standards are expanding into various areas. Considering this situation of time and frequency standards, CRL is trying to contribute to the time and frequency domain. Figure 6 shows the projection of research on time and frequency standards at CRL.

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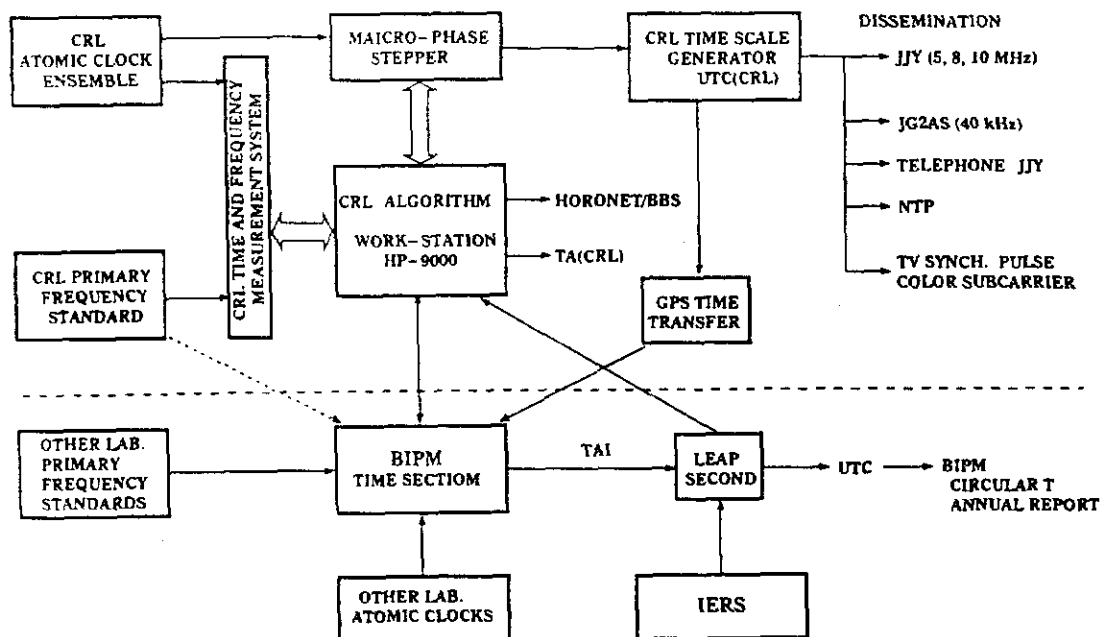


Figure 1 Real-time UTC(CRL) Generation System and Relation between TAI and UTC.

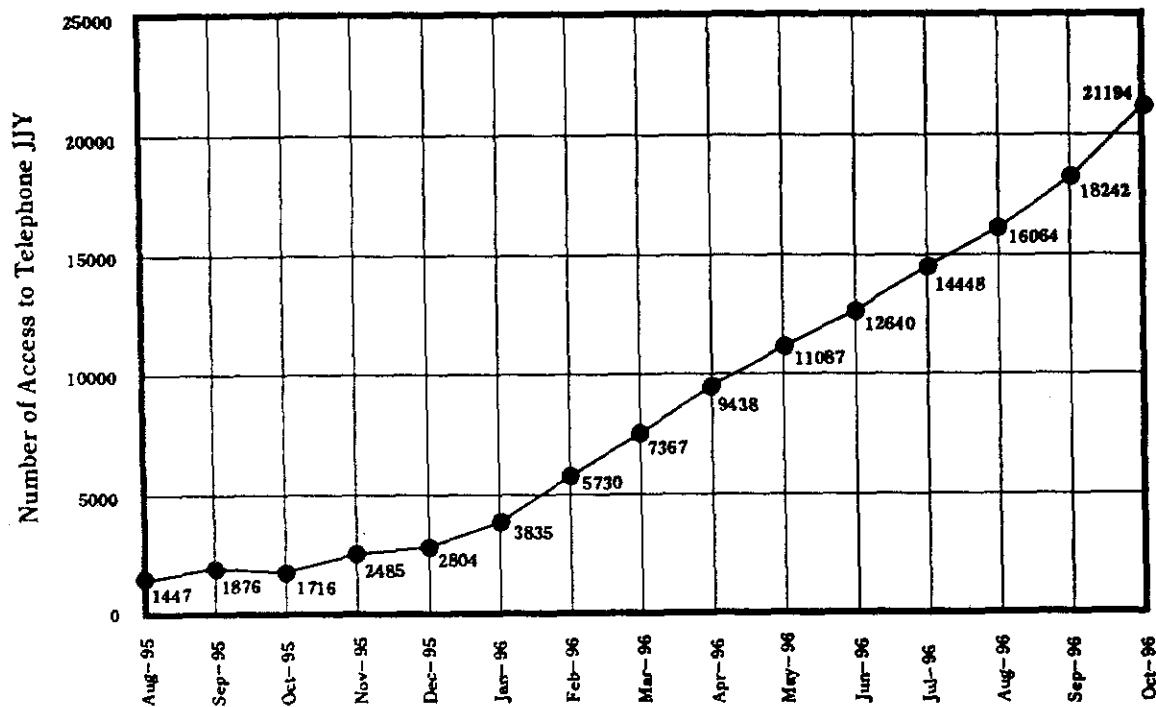


Figure 2 Number of Access to Telephone JJY System

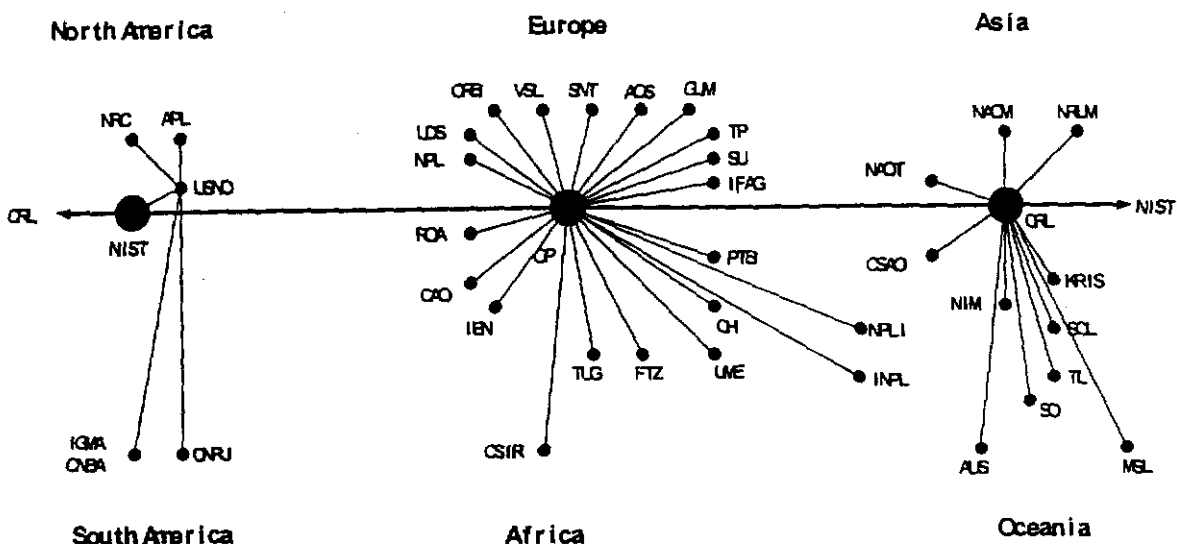


Figure 3 GPS Time Transfer Network for TAI Calculation (from brochure of BIPM).

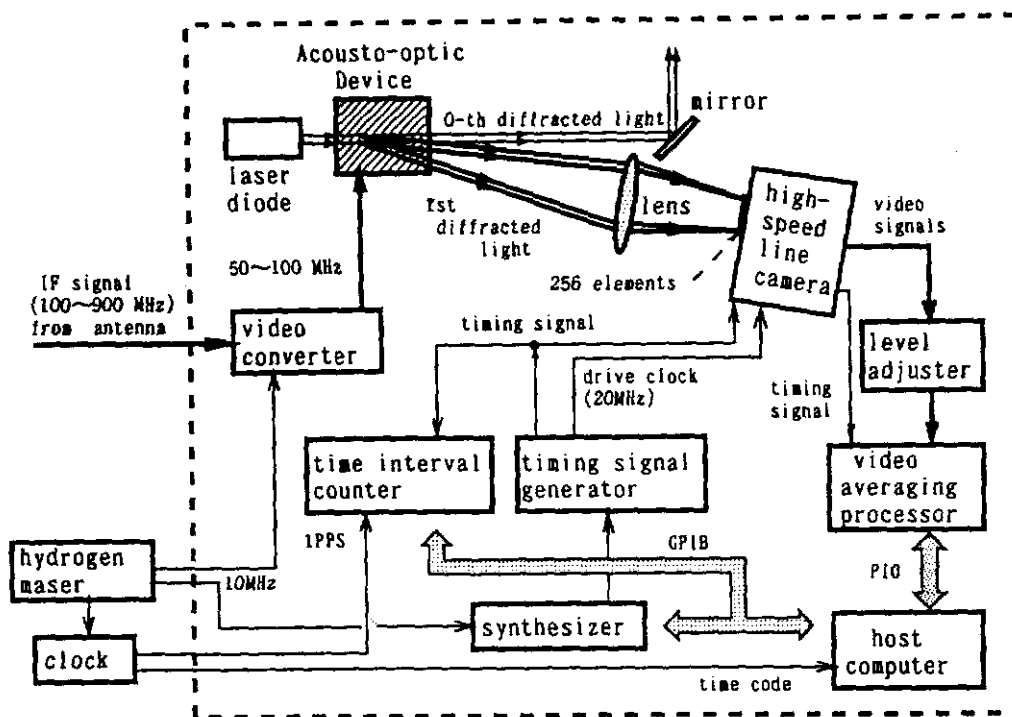


Figure 4 Schematic Diagram of the Pulsar Timing Measurement System using AOS.

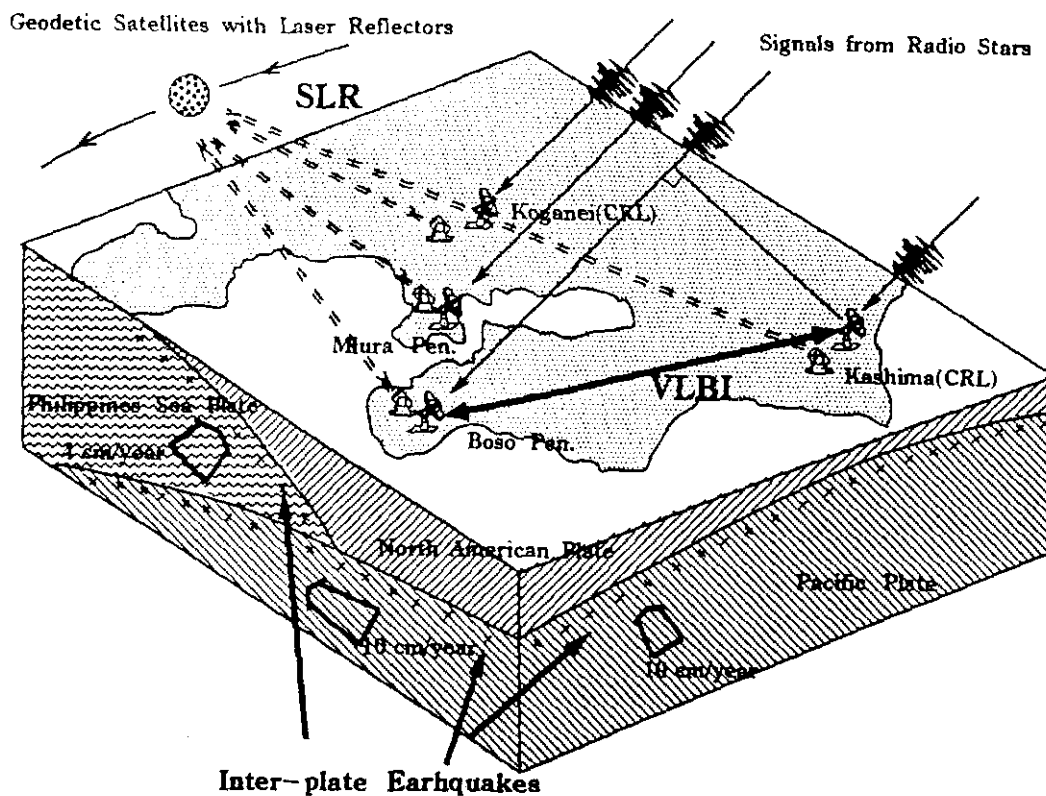


Figure 5 Crustal Deformation Monitoring System for the Tokyo Metropolitan Area.

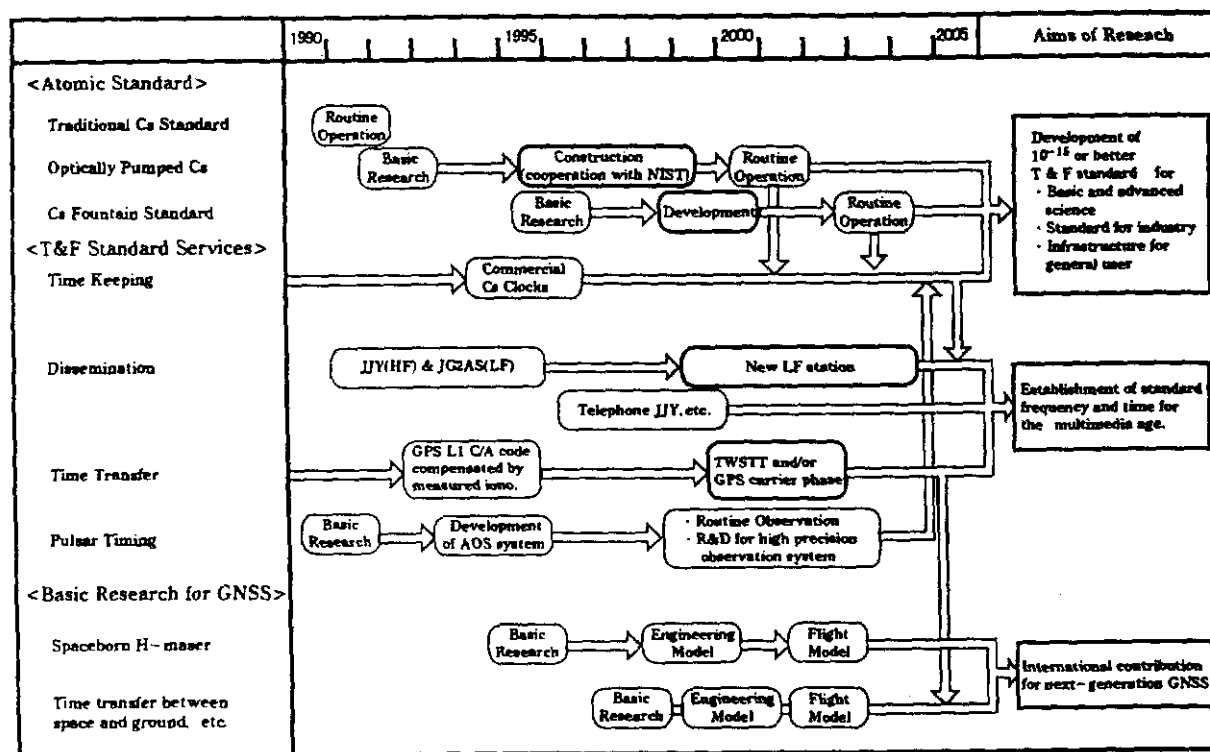


Figure 6 Projection of Research on Time and Frequency Standards at CRL.

Questions and Answers

SIGFRIDO LESCHIUTTA (IEN, ITALY): Your communication research laboratory is a laboratory belonging to a ministry as a public laboratory?

MICHITO IMAE: The Ministry of Post and Telecommunication.

SIGFRIDO LESCHIUTTA: Concerning the LF station on 40 kHz, what kind of signals are you planning to radiate? Also, time codes.

MICHITO IMAE: On the present LF station, we also transmit a time code. But the transmission power is not strong enough to cover all of Japan.

RICHARD KEATING (USNO): The Japanese Communication Satellite, the JC-SAT, as you call it, I notice has a wide footprint over Eastern Australia and New Zealand. Is the down link a spread-spectrum technique and, if so, who makes the modems?

MICHITO IMAE: It is only a communication satellite which has a transponder and we transmit such a signal. It can operate in spectrum mode.

SIGFRIDO LESCHIUTTA: I have a third question. Could you please present the last slide? You were speaking about your research on a spaceborne H-maser. Could you elaborate a bit since the problem arose this morning?

MICHITO IMAE: In Japan, as Dr. Busca mentioned this morning, there are several plans to construct a new generation of the GNSS by the Agency of Science and Technology, NASADA, and our ministry. The Japanese Committee for Space Development decided to gather all of these plans and discuss how Japan can contribute to this domain. So at present we are discussing within the committee the basic technology for an onboard clock and research work. We will start next year in my laboratory.